

The Fermi blazars divide

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ABSTRACT

Flat Spectrum Radio Quasars (FSRQs) and BL Lac objects detected in the first three months of the *Fermi* survey neatly separate in the γ -ray spectral index vs γ -ray luminosity plane. BL Lac objects are less luminous and have harder spectra than broad line blazars. We suggest that this division has its origin in the different accretion regimes of the two classes of objects. Using the γ -ray luminosity as a proxy for the observed bolometric one we show that the boundary between the two subclasses of blazars can be associated with the threshold between the regimes of optically thick accretion disks and of radiatively inefficient accretion flows, which lies at an accretion rate of the order of 10^{-2} the Eddington rate. The spectral separation in hard (BL Lacs) and soft (FSRQs) objects can then result from the different radiative cooling suffered by the relativistic electrons in jets propagating in different ambients. We argue that the bulk of the most luminous blazars already detected by *Fermi* should be characterised by large black hole masses, around 10^9 solar masses, and predict that lowering the γ -ray flux threshold the region of the α_γ - L_γ plane corresponding to steep spectral indices and lower luminosities will be progressively populated by FSRQs with lower mass black holes, while the region of hard spectra and large luminosities will remain forbidden.

Key words: BL Lacertae objects: general — quasars: general — radiation mechanisms: non-thermal — γ -rays: theory

1 INTRODUCTION

The Large Area Telescope (LAT) on board the *Fermi Gamma Ray Space Telescope* (*Fermi*) revealed more than one hundred blazars with a significance larger than 10σ in the first three months of operation (Abdo et al. 2009a, hereafter A09). Of these, 57 are classified as flat spectrum radio quasars (FSRQs), 42 as BL Lac objects, while for 5 sources the classification is uncertain. Including 2 radio-galaxies the total number of extragalactic sources amounts to 106. Redshifts are known for all FSRQs, for 30 BL Lacs, for 1 source of uncertain classification and for the two radio-galaxies, for a total of 90 objects. Particularly significant is the large number of BL Lac objects present in the *Fermi* sample, which allows for the first time an objective comparison of their γ -ray properties (spectral shape and luminosity) with those of FSRQs.

A direct result of the first *Fermi* blazar sample, discussed by A09, is the finding of correlations between their γ -ray and radio fluxes/luminosities and between the photon spectral index Γ_γ in the *Fermi* energy band and their radio luminosity. In the latter plane, as noted by A09, blazars seem to define a trend, of increasing Γ_γ (softness) for increasing radio luminosity, with BL Lac objects falling at the lower end of this trend. However within each of the two separate populations these correlations are not highly significant.

In this letter we consider BL Lacs and FSRQs as part of a

unified blazar population, at variance with the approach of A09. Using the γ -ray rather than the radio luminosity (the former being more indicative of the bolometric power), we discuss the spectral index/ γ -ray luminosity plane where BL Lacs and FSRQs occupy different regions. We then propose a simple scenario to explain why there is a rather well defined boundary between BL Lacs and FSRQs. In our scheme all blazars are essentially similar and their different observed properties result from the different accretion rates feeding their central engines. We show that the observed γ -ray spectral index dependence on γ -ray (as well as radio) luminosity can be naturally explained in the above context. Finally we discuss some implications and predictions of the proposed scenario.

We adopt a cosmology with $h = \Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$.

2 THE GAMMA-RAY SLOPE VS LUMINOSITY PLANE

We derived the γ -ray luminosities for all the blazars with known redshift detected by *Fermi* in the three months survey (excluding radio galaxies) using the fluxes named F_{100} in Table 3 of A09, characterising their “average” observed flux (between August 4 and October 30 2008). The luminosities were computed according to:

$$L_\gamma = 4\pi d_L^2 \frac{S_\gamma(\nu_1, \nu_2)}{(1+z)^{1-\alpha_\gamma}} \quad (1)$$

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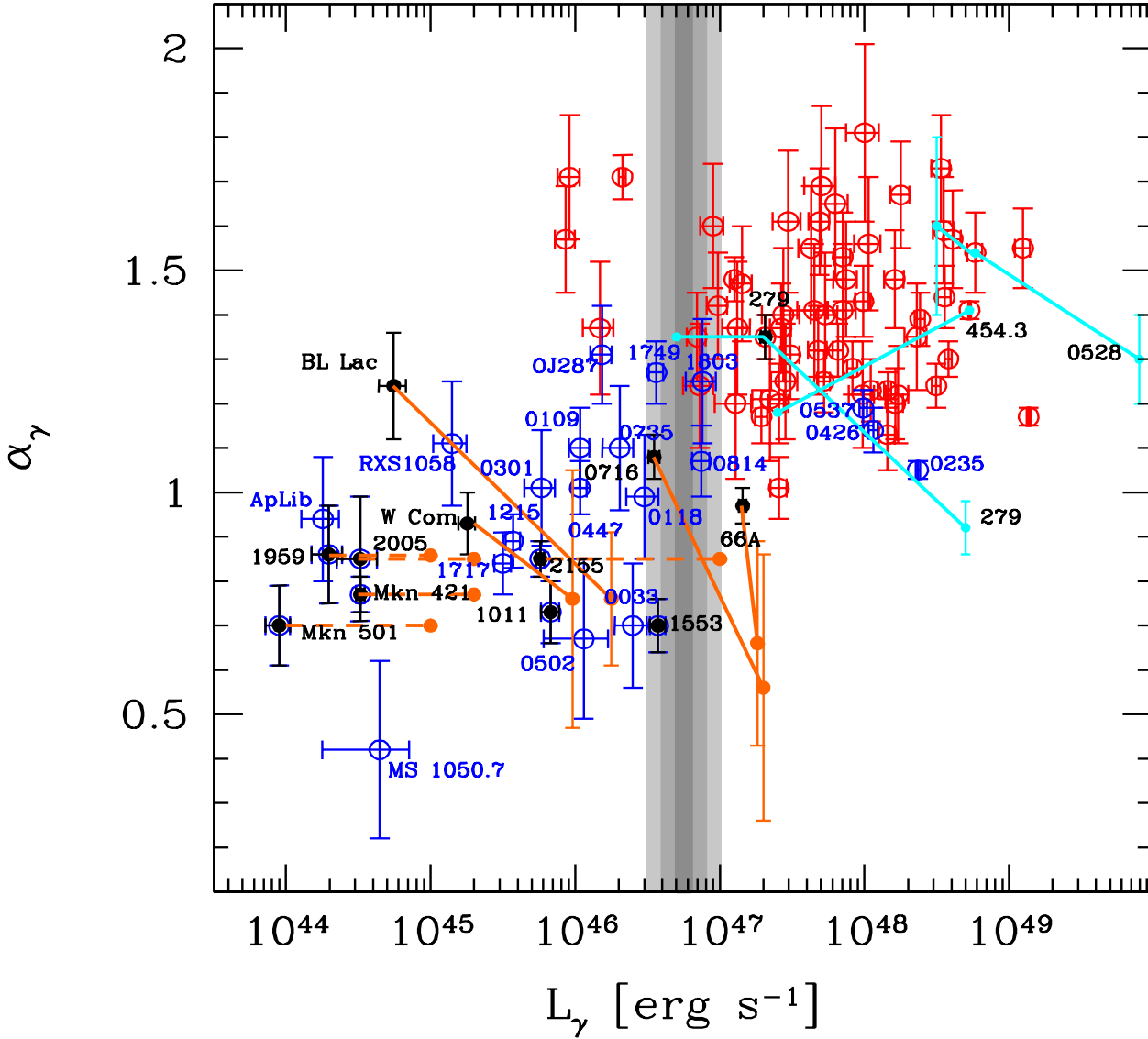


Figure 1. Energy spectral index vs γ -ray luminosity for all blazars in the list of Abdo et al. (2009a). Blue and red points are BL Lacs and FSRQs, respectively. Black symbols correspond to sources already detected in the TeV band (they are all BL Lacs but 3C 279). Labels identify all BL Lac objects, 3C 279 and other 2 FSRQs. For several BL Lac objects and for the 3 labelled FSRQs we show the observed range of γ -ray luminosity and spectral index, using past EGRET or *AGILE* observations. This is indicated by a solid line segment (dashed when the spectral index is unknown, and we chose the same index as observed by *Fermi*). For 0716+714, the high luminosity point corresponds to *AGILE* observations (Chen et al. 2008) with a large error on the spectral index (shown by the large error bar). The grey stripes at about $L_\gamma = 10^{47}$ erg s $^{-1}$ mark the divide between BL Lac objects and FSRQs.

where d_L is the luminosity distance, $\alpha_\gamma = \Gamma_\gamma - 1$, $S(\nu_1, \nu_2)$ is the γ -ray energy flux between the frequencies ν_1 and ν_2 , calculated from the photon flux $F_\gamma(E > 100 \text{ MeV})$ [ph cm $^{-2}$ s $^{-1}$] as:

$$\begin{aligned} S_\gamma(\nu_1, \nu_2) &= \frac{\alpha_\gamma h \nu_1 F_\gamma}{1 - \alpha_\gamma} \left[\left(\frac{\nu_2}{\nu_1} \right)^{1 - \alpha_\gamma} - 1 \right] & \alpha_\gamma \neq 1 \\ S_\gamma(\nu_1, \nu_2) &= h \nu_1 F_\gamma \ln(\nu_2 / \nu_1) & \alpha_\gamma = 1 \end{aligned} \quad (2)$$

Setting $\nu_1 = 2.42 \times 10^{22}$ Hz (0.1 GeV) and $\nu_2 = 2.42 \times 10^{24}$ Hz (10 GeV), and $F_\gamma = 10^{-8} F_{\gamma,-8}$ ph cm $^{-2}$ s $^{-1}$, we have (in units of erg cm $^{-2}$ s $^{-1}$):

$$S_\gamma(0.1, 10) = 1.6 \times 10^{-12} \frac{\alpha_\gamma F_{\gamma,-8}}{1 - \alpha_\gamma} [100^{1 - \alpha_\gamma} - 1] \quad \alpha_\gamma \neq 1$$

$$S_\gamma(0.1, 10) = 7.38 \times 10^{-12} F_{\gamma,-8} \quad \alpha_\gamma = 1 \quad (3)$$

Fig. 1 shows the energy spectral index α_γ given by A09 as a function of L_γ between 0.1 and 10 GeV calculated according to Eqs. 1–3. Blue and red symbols correspond to BL Lac objects and FSRQs, respectively, while black symbols indicate sources also detected in the TeV band¹. The latter are all BL Lac objects except for 3C 279, which is an intermediate object with Ly α emerging in low states (Koratkar, Pian & Urry 1998; Pian et al. 1999).

¹ We have included 0716+714 as a TeV detected BL Lac (Teshima 2008), although it is not noted as such in A09. Therefore the total number of *Fermi* bright blazar that have been also detected in the TeV band is 12.

Blazars are highly variable sources, especially at high energies. To illustrate the possible range of variability, for a few sources we connect with a line segment the spectral index and γ -ray luminosity observed by *Fermi* to the values observed in the past by the EGRET instrument onboard the *Compton Gamma Ray Observatory* satellite (Nandikotkur et al. 2007), or observed by the *AGILE* satellite. Note that variable sources often “move” orthogonally to the correlation defined by the ensemble of sources, i.e. they become harder when brighter (with the exception of 3C 454.3).

Moreover, for some of the sources detected in the TeV range, we can infer the level of γ -ray activity during high states of TeV emission (assuming that the flux in the *Fermi* band would have been about the same as the TeV flux). For these sources we indicate the range of luminosity variability by dotted line segments, maintaining the spectral index measured by *Fermi* for both states.

As can be seen, the high and the low γ -ray states of single sources can be dramatically different. This implies that the distribution in luminosity within each blazar class is largely affected by the variability of the sources.

The α_γ - L_γ plane (Fig. 1) strongly suggests a separation of the two groups in regions defined by $\alpha_\gamma > 1.2$, $L_\gamma > 10^{47}$ erg s⁻¹ for FSRQ and $\alpha_\gamma < 1.2$, $L_\gamma < 10^{47}$ erg s⁻¹ for BL Lacs. At the same time there is continuity between the two blazar subclasses in that their properties overlap at intermediate values of both spectral index and γ -ray luminosity.

The separation in spectral indices, already evident in Fig. 9 of A09, occurs at $\alpha_\gamma \simeq 1.2$. Only 5 FSRQs have spectra flatter than 1.2, and only 5 BL Lacs have spectra steeper than 1.2. The LAT γ -ray data have been systematically analysed by A09 fitting a single power law model to the spectral data of each source. In many cases the intrinsic spectral shape could be more complex (i.e. a curved spectrum). Fig. 10 of A09 shows as illustrative examples the γ -ray SEDs of 3C 454.3 (energy index $\alpha_\gamma = 1.41 \pm 0.02$), AO 0235+164 ($\alpha_\gamma = 1.05 \pm 0.02$) and Mkn 501 ($\alpha_\gamma = 0.70 \pm 0.09$). In the first two cases the data are not well represented by the single power-law model, showing significant curvature and indicating SED peaks below 100 MeV for 3C 454.3 and between 1 and 10 GeV for AO 0235+164, while Mkn 501 shows a very hard γ -ray SED implying that the SED peak should be above 100 GeV. It is therefore reasonable to assume that the spectral index measured by *Fermi* is a proxy for the peak energy of the γ -ray SED, at least in a statistical sense. Thus the γ -ray SEDs of most FSRQs, with $\alpha_\gamma > 1.2$, should peak at or below the low energy range of the *Fermi* energy window, at lower peak energies than those characterising most of BL Lacs objects. As expected, BL Lacs detected in the TeV band tend to be harder than other BL Lacs (with the exception of BL Lac itself), indicating a high peak energy, in turn necessary to detect them in the TeV band.

The separation in γ -ray luminosity between BL Lac objects and FSRQs is also striking. There are only 3 BL Lac objects (PKS 0537-441 with $z = 0.892$, AO 0235+164 with $z = 0.94$ and PKS 0426-380 with $z = 1.12$) with $L_\gamma > 10^{47}$ erg s⁻¹. The redshifts of these 3 sources are among the highest of the BL Lac sub-sample (see Fig. 16 of A09). Moreover, *all* three sources *do have broad lines*, visible in their low emission states (see Sbarufatti et al. 2005 for PKS 0426-380; Pian et al. 2002 for PKS 0537-441; Raiteri et al. 2007 for AO 0235+164).

In principle, the two blazar classes could be separated because of a different average Doppler boosting, but all indications so far for the γ -ray emitting BL Lacs and FSRQs suggest instead similar values of the Doppler boosting, with the exception of TeV emitting BL Lacs, requiring a stronger boost (and thus a smaller viewing

angle). These inferences come from superluminal motion (Jorstad et al. 2001; Kellerman et al. 2004), direct modelling of their SED (e.g. Konopelko et al. 2003; Finke, Dermer & Böttcher 2008) and very rapid TeV variability (e.g. Begelman, Fabian & Rees 2008; Ghisellini & Tavecchio 2008b). Thus the idea that the luminosity sequence of BL Lacs and FSRQs is due to larger viewing angles for BL Lacs is disfavoured.

2.1 The blazar sequence in γ -rays

The SEDs of blazars show two main components: the first one, peaking between the far infrared and the X-ray band, is unanimously attributed to synchrotron emission; the second, peaking between 10 MeV–100 GeV, is widely attributed to the Inverse Compton process involving the same electrons producing the synchrotron component (e.g. Maraschi et al. 1992; Bloom & Marscher et al. 1996; Sikora et al. 1994; Dermer & Schlickeiser 1993).

Fossati et al. (1998) and Ghisellini et al. (1998) proposed that the SEDs of blazars form a “spectral sequence” whereby the peaks of the two components are governed by luminosity, and are at higher energies for lower luminosities². This was interpreted in terms of a stronger radiative cooling for more powerful sources, resulting in smaller energies of the electrons emitting at the peaks. As discussed above, a high energy peak above ~ 10 GeV corresponds to a hard spectrum in the *Fermi* range (rising, in νF_ν), while a peak frequency below ~ 1 GeV corresponds to a soft spectrum in the *Fermi* range. Therefore the trend apparent in the α_γ - L_γ plane strongly supports the “sequence” concept, which was proposed on the basis of radio and X-ray selected samples, where only a fraction of objects had γ -ray data. Fig. 1 represents the γ -ray selected version of the blazar sequence.

Single objects, instead, often behave in the opposite way (i.e. harder when brighter). This can be explained, if, in single objects, an unchanged cooling faces a fast increasing heating (i.e. injection of more energetic electrons), shifting the typical electron energies to larger values. In the next section we present a possible interpretation of the separation of FSRQs and BL Lacs in the α_γ - L_γ plane.

3 INTERPRETATION OF THE BL LAC – FSRQ DIVIDE

The neat separation between BL Lacs and FSRQs in the α_γ - L_γ plane together with their close contiguity are really remarkable. A possible interpretation could simply be to assume two independent populations with different physical conditions as to the origin, propagation and radiative properties of their jets. This however would not account for the contiguity which should be coincidental. Figs. 11 and 17 of A09 (α_γ vs z and L_γ vs z) indicate that the separation and the contiguity behaviour of the two blazar sub-classes exist also in these planes.

Building on previous work on the systematic properties of blazars we suggest that this division has a physical origin, related to the different mass accretion rates onto the central engine. We first summarise some preliminary steps as follows:

(i) Radiative models allow to estimate the total jet power P_j carried in the form of bulk and internal energy of protons, electrons and magnetic field. For powerful FSRQs a fraction $\epsilon \sim 0.1$ of P_j

² The original idea considered the luminosity as the main parameter governing the blazar sequence, while the refined version (Ghisellini & Tavecchio 2008a) considers the luminosity in Eddington units.

is radiated at short distances (i.e. hundreds of Schwarzschild radii) from the central black hole. This fraction can be larger for BL Lacs (Celotti & Ghisellini 2008).

(ii) In powerful FSRQs, P_j is about one order of magnitude larger than the *observed* accretion disk luminosity L_d (Maraschi 2001; Maraschi & Tavecchio 2003; Celotti & Ghisellini 2008; Ghisellini & Tavecchio 2008a; see also the earlier results of Rawlings & Saunders 1991). For a “standard” Shakura & Sunyaev (1973) accretion disk, $L_d = \eta \dot{M} c^2$, where \dot{M} is the accretion rate, with $\eta \sim 0.1$. It follows that the jet power P_j is of the same order as the accretion power $\dot{M} c^2$. This is also supported theoretically (at least at the “dimensional level”) since, even if the black hole rotation played an essential role as in the Blandford & Znajek (1977) model, accretion would still be needed to provide the magnetic field necessary to extract the rotational energy. We then assume that the (order of magnitude) equality $P_j \simeq \dot{M} c^2$ has general validity for strong jets, being aware of the significant uncertainties associated with it.

(iii) Finally, the γ -ray luminosity dominates the electromagnetic output of powerful FSRQs and is at least a sizeable fraction of it in less powerful BL Lacs. The observed $L_\gamma \sim \Gamma^2 \epsilon P_j$ (the factor Γ^2 accounts for light aberration).

Adopting the relations above, it then follows that the maximum observed L_γ should correspond to the largest black hole masses accreting at the maximum, Eddington, rate

$$L_{\gamma, \max} \sim \epsilon \Gamma^2 \dot{M}_{\text{Edd}} c^2 \sim 1.5 \times 10^{47} \epsilon \Gamma^2 M_9 \text{ erg s}^{-1} \quad (4)$$

where M_9 is the mass of the black hole in units of 10^9 solar masses. The γ -ray luminosity of the most luminous FSRQs (Fig. 1) is of the order of several $\times 10^{48} \text{ erg s}^{-1}$, corresponding to $\epsilon \Gamma^2 M_9 \sim 30$.

Fig. 1 shows a divide at a γ -ray luminosity roughly a factor 100 below the maximum (grey stripes). Maintaining the same value of $\epsilon \Gamma^2 M_9 \sim 30$, we conclude that the jet power, hence the accretion rate, is a factor ~ 100 below the maximum. Therefore, at the divided luminosity, the accretion rate is of order:

$$\dot{M}_{\text{div}} \approx 10^{-2} \dot{M}_{\text{Edd}} \quad (5)$$

Crucial, in this simple derivation, is the assumption that the most luminous FSRQs and the most luminous BL Lacs (excluding the three “outliers” mentioned above) have the same factor $\epsilon \Gamma^2 M$, and in particular the same black hole mass M . This is likely, since we are dealing with the most luminous objects of the two classes (this also applies to the original blazar sequence). Indeed, for TeV BL Lacs, which span the entire region of BL Lacs, the available estimates indicate high black hole masses (e.g. Wagner 2008, Ghisellini & Tavecchio 2008a), in some cases exceeding $10^9 M_\odot$. In the case of FSRQs (more luminous than BL Lacs) *Fermi* could have already started to explore smaller black hole masses. In fact, the object PMN 0948+0022 ($\alpha_\gamma = 1.6 \pm 0.14$ and $L_\gamma \sim 10^{47} \text{ erg s}^{-1}$) is a NLSy1, with a black hole mass around $10^8 M_\odot$ (see Abdo et al. 2009b and Zhou et al. 2006). This easily accounts for the few FSRQs with $L_\gamma < 10^{47} \text{ erg s}^{-1}$ (i.e. they should have black hole masses smaller than the rest of FSRQs).

The derived value of \dot{M}_{div} is naturally interpreted as due to the transition between different accretion regimes: for high accretion rates, in Eddington units, a standard optically thick geometrically thin, radiatively efficient Shakura–Sunyaev (1973) disk is formed producing a luminous Broad Line Region through which the jet must propagate suffering strong radiative losses. For $\dot{M} \sim \dot{M}_{\text{Edd}}$ some of the disk luminosity could be advected into the black hole,

resulting in $\eta < 0.1$, but this would not affect the presence of the BLR, nor the power of the jet.

When $\dot{M} \ll \dot{M}_{\text{Edd}}$ the accretion flow becomes optically thin and radiatively inefficient and could be described as an ion supported torus (Rees et al. 1982) or an advection dominated accretion flow (ADAF, see e.g. Narayan, Garcia & McClintock 1997), an adiabatic inflow–outflow (ADIOS, Blandford & Begelman 1999) or a convection dominated flow (CDAF, Narayan, Igumenshchev & Abramowicz 2000). In the latter case despite the uncertainties in the dynamics of the flow the surrounding region will certainly be deprived of photons with respect to the high accretion rate regime, thus justifying the absence of broad emission lines and the reduced radiative losses for the propagating jet.

Since FSRQs are associated with radio sources with FR II morphology while BL Lac objects are usually found in FR Is, the same critical rate should separate the two parent populations. And indeed the finding by Ledlow & Owen (1996) that the radio luminosity threshold between the two classes depends on the optical magnitude of the bulge of the host galaxy (i.e. on the mass of the central black hole), was interpreted by Ghisellini & Celotti (2001) in terms of a critical accretion rate, coincident in value with what found here (see also more recent work by Xu, Cao & Wu 2009).

4 DISCUSSION AND CONCLUSIONS

The spectral shape/ γ -ray luminosity plane revealed a clear separation between FSRQs and BL Lac objects. Moreover, there is a well defined trend, with BL Lac objects being harder and less luminous than FSRQs. At the first order, this strongly confirms the idea that blazars obey a spectral sequence, controlled by the bolometric luminosity, of which the γ -ray one is good proxy.

The other striking feature is the little overlap, in γ -ray luminosity, of the two classes of blazars. We suggest that this has a physical origin, and have interpreted it in terms of a critical accretion rate \dot{M}_{div} . Below \dot{M}_{div} accretion becomes radiatively inefficient, the corresponding ionising flux becomes weaker, making weaker (or absent) broad emission lines. These are BL Lac objects. Their jets thus propagate in a medium starved of external radiation (weak disk, weak lines), and this makes the emitting electrons accelerated in the jet to cool less, and to reach very high energies. Their emitted high energy spectrum, produced mainly by the synchrotron self-Compton mechanism, is less luminous and harder than in FSRQs. The latter sources in fact have a radiatively efficient accretion disk and a corresponding “standard” broad line region. If the jet dissipates most of its power within the broad line region, then the emitting electrons will efficiently cool (mostly by external Compton), will reach only moderate energies, and will produce a high energy peak below 100 MeV. This scenario is in perfect agreement with the analogous division proposed for radio–galaxies, that in turn are thought to be the progenitors of BL Lacs (FR I) and FSRQs (FR II).

According to this idea the power of the jets in all blazars is proportional to the accretion rate, that can change in a continuous way from one objects to the other (and even in single objects). The observed discontinuity between BL Lacs and FSRQs is the result of a discontinuity in the accretion regime occurring within a rather narrow range of \dot{M} (from standard to radiatively inefficient). Thus, despite the different “look” of FSRQs and BL Lacs, they all belong to a sequence of jet powers. From this point of view, it is therefore reasonable to treat them as a single class.

Evidences that P_j is of the same order of $\dot{M} c^2$ can be traced back to Rawlings & Saunders (1991), and since then confirmed by

several works (e.g. Celotti et al. 1997; Cavaliere & D’Elia 2002; D’Elia, Padovani & Landt 2003; Maraschi & Tavecchio 2003; Sambruna et al. 2006; Allen et al. 2006; Celotti & Ghisellini 2008; Kataoka et al. 2008). Also, the discovery that large scale jets of powerful blazars are strong X-ray emitters, detectable and resolvable by the *Chandra* satellite, offered a novel way to measure P_j , confirming that in these sources the jet power is not only of the same order than $\dot{M}c^2$, but it is also constant all along the jet (Tavecchio et al. 2004; Cheung et al. 2006).

Also the idea that the differences between powerful FSRQs (and their FR II radio–galaxy counterpart) and BL Lacs (and FR I radio–galaxies) is due to a difference in the accretion regime of their disks has been already put forward (Ghisellini & Celotti 2001; Jester 2005) and used to explain the different cosmic evolution of these two classes of blazars (see e.g. Böttcher & Dermer 2002; Cavaliere & D’Elia 2002). Interestingly, also in radio–quiet AGNs there is evidence that the relative strength of the broad emission lines is a function of the accretion disk luminosity in Eddington units, with the possibility of a very weak BLR for accretion rates below $10^{-2}L_{\text{Edd}}$ (for review, see Ho 2008). What is new, in this paper, is the interpretation, in terms of accretion rates, of the intriguing separation of FSRQs and BL Lacs detected by *Fermi* in the α_γ – L_γ plane. A (likely) cosmic evolution of \dot{M} , while not affecting our results, would account for the existing hints of a negative and positive cosmic evolution of BL Lacs and FSRQs, respectively (see, e.g. A09).

There are a few checks to put our scenario on test. Perhaps the simplest is to have clues on the black hole masses of the most luminous BL Lacs and FSRQs. We predict them to be of the same order. A related check is to directly find the accretion disk luminosity for the most luminous FSRQs. If also the black hole mass is known or derived, then we can test if their disk are indeed emitting close to the Eddington limit, as we have assumed.

Although exceptions exist for any rule, it should be interesting to study in more detail the three BL Lacs that are “outliers”, lying in the FSRQ–region. Since they do have broad lines, we propose that they are normal FSRQs whose non–thermal continuum is so enhanced by beaming that it hides the broad lines. If this is the case, the FSRQs/BL Lacs division, now in terms of the line equivalent width, could be substituted by a more physical division in terms of broad line luminosity.

In just 3 months of all sky survey (and selecting only the brightest ones), *Fermi* has already doubled the number of known γ –ray emitting blazars. Soon we will have to deal with thousands of them. Since blazars are very variable, perhaps spending a limited amount of time in high state, continuing to patrol the all sky will surely reveal exceptional states of sources otherwise unnoticeable. On the other hand, the increase in sensitivity due to the increased exposure time will allow to find many less powerful jets and less luminous γ –ray luminosities. The divide will then be not as clear as it is now, since many FSRQs (with black hole masses below $10^9 M_\odot$) will occupy the region below $L_\gamma = 10^{47} \text{ erg s}^{-1}$. On the other hand, the prediction is that no or very few BL Lacs will be found above this limit. These improved samples will surely be useful to confirm, or reject, or constrain our scenario.

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